AIDIC *Conference Series*, Vol. 10, 2011
Editor Sauro Pierucci
DOI: 10.3303/ACOS1110011

ISBN 978-88-95608-58-7 ISSN 2036-5969

SAFETY OF LNG REGASIFICATION TERMINALS: THE BLUE BOOK APPROACH

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The iNTeg-Risk research project (http://www.integrisk.eu-vri.eu/), carried out under the 7th Framework Program (EU Grant number CP-IP-213345-2), has the purpose to promote R&D activities aimed at the improvement of the management of emerging risks related to new materials and technologies. Within the project, a specific activity is dedicated to the development of innovative approaches for the assessment of safety of LNG terminals, both offshore and onshore. A specific Guideline (“Blue Book”) was issued in order to summarize new developments and available data, methods and techniques for the assessment of LNG safety.

The present paper will focus on the specific contribution provided by Italian partners of the project to the “Blue Book”. In particular, the work carried out on the assessment of specific scenarios related to LNG terminals and on consequence assessment models will be presented. A relevant effort was dedicated to the systematic exploration of credible accident scenarios that may follow external events involving LNG terminals. The results were used to consider the application of improved consequence assessment models both for the prediction of NG dispersion following release and for the Rapid Phase Transition that may be caused by massive LNG releases over water.

1. INTRODUCTION

The Integ-Risk research project (http://www.integrisk.eu-vri.eu/), carried out under the 7th Framework Program (EU Grant number CP-IP-213345-2), has the purpose to promote R&D activities aimed at the improvement of emerging risk management with specific reference to new materials and technologies. Within the project, an activity is dedicated to the development of innovative approaches for safety assessment of LNG terminals, both offshore and onshore.

Natural gas supply as LNG will play an increasing role in the European energy market, being expected to increase up to 70% in 2020. The number of regasification plants in Europe is going to increase, and new technologies for offshore terminals are finding an increasing application. New and emerging risks related to floating or off-shore installations are not fully explored to date and the hazards associated to these installations is

Please cite this article as: Cozzani V., Rota R., Tugnoli A., Busini V., Bubbico R., Salzano E. and Uguccioni G., (2011), Safety of lng regasification terminals: the blue book approach, AIDIC Conference Series, 10, 95-104 DOI: 10.3303/ACOS1110011

highly perceived by the population. A specific Guideline ("Blue Book") was thus issued, in order to summarize data, new developments, methods and techniques for the assessment of LNG safety gathered within the project. The present paper is focused on the specific contribution provided by Italian partners of the iNTeg-Risk project to the "Blue Book". In particular, the work carried out on the assessment of specific scenarios related to LNG terminals and on updated consequence assessment models will be presented. A relevant effort was dedicated to the systematic exploration of credible accident scenarios that may follow external events involving LNG terminals. The results were used for the application of improved consequence assessment models both for the prediction of NG dispersion following release and for Rapid Phase Transition that may be caused by massive LNG releases over water.

Table 1: DyPASI procedure steps

Steps	Bow-tie diagram generation in MIMAH (Delvosalle et al., 2006)	Bow-tie diagram upgrade in DyPASI procedure
0	\	Pre-analysis aiming at the identification of potential atypical incident scenarios and at the creation of proper diagram branches describing related bow ties.
1	Drawing up a list of hazardous substances present in the plant	This step allows the evaluation of additional hazards of substances, not described by risk phrases but defined in the pre-analysis
2	Definition of critical events	The purpose of this step is to include the critical events outlined in the pre-analysis or to identify them among those proposed by MIMAH.
3	Construction of event trees	This step allows the inclusion of critical event consequences previously considered or their identification by the event trees obtained by MIMAH, on the basis of what outlined in the pre-analysis.
4	Construction of fault trees	This step allows the inclusion of the cut-set of the critical events previously considered or their identification in the fault trees obtained by MIMAH, on the basis of what outlined in the pre-analysis.
5	Definition of safety barriers	Once defined bow-tie diagrams, safety barriers are studied. This step aims at the identification of the existing safety barriers and at the definition of new useful safety barriers.

2. HAZARD IDENTIFICATION TECHNIQUES

2.1 State of the art

The analysis of the current state-of-the-art, as described by Technical Standards (e.g. CEN, 1996, 1997, 2001, 2006, 2007, 2008; NFPA, 2006), Safety Reports (for operative and proposed LNG terminals) and Technical Literature (e.g. Hightower et al. 2004), reveals that quite conventional techniques are proposed in hazard identification for LNG terminals. These include hazard and operability studies (HAZOP), failure mode and effect analysis (FMEA), event tree methods (ETM), fault tree methods (FTM), etc. Thus, no specific method was identified. Moreover, the analysis of the current state-of-the-art in hazard identification for LNG plants evidenced the presence of gaps and “grey areas”. The key issues identified in gap analysis concerned the availability of a guided approach to the systematic extension of the consolidated knowledge to innovative design solutions, the assessment of external threats, and the inclusion of “unknown known” hazards from the analysis of past accidents and near-misses.

A portfolio of improved hazard identification methods was thus developed to bridge the gaps in the application of hazard identification techniques to LNG terminal technologies. The proposed methods represent mostly improvements and integrations of traditional tools, specifically developed to address specific gaps identified.

2.2 Dynamic Procedure of Atypical Scenarios Identification (DyPASI)

The Dynamic Procedure for Atypical Scenarios Identification (DyPASI) consists in a self-learning method for the systematization of information from past accidents and near-misses and the generation of bow-tie branches, consistently with the methodologies developed in the ARAMIS Project (Delvosalle, 2004).

DyPASI can be applied to the identification of atypical hazards related to the safety of new and alternative technologies for LNG regasification. A hazard can be classified as “atypical” when it cannot be captured by common hazard identification techniques because deviating from normal expectations. The aim of DyPASI is to make easier and systematic the inclusion of atypical incident scenarios in “hazard identification” processes, which are often unable to capture low probability events or events for which limited knowledge exists. The method is based on a general horizon screening, which can make aware of potential hazards and incident scenarios related to substances, equipments and industrial process considered. The main goal is to identify the specific accidental chains and to infer general accidental patterns. A more detailed description of this methodology can be found elsewhere (Paltrinieri et al., 2010).

Thus, DyPASI is a procedure able to consider early warnings concerning atypical incident scenarios coming from past incidents, inherent studies or general concern. This procedure was developed to support the bow-tie diagrams MIMAH methodology and should be applied only once general MIMAH bow-tie diagrams for the case being studied were built. The procedure allows also a double check of the hazard identification process.

An atypical incident scenario is the result of a sequence of events, not necessarily all atypical. Thus, in order to properly describe an atypical incident scenario, both atypical and non-atypical events should be added or identified, step by step, in the process of bow-tie construction. Table 1 shows all the steps of the procedure and relates them to the corresponding MIMAH phases of diagram generation. Figure 1 shows a chain of events identified by the DyPASI procedure. Similar data allow for the integration of fault chains and accident scenarios

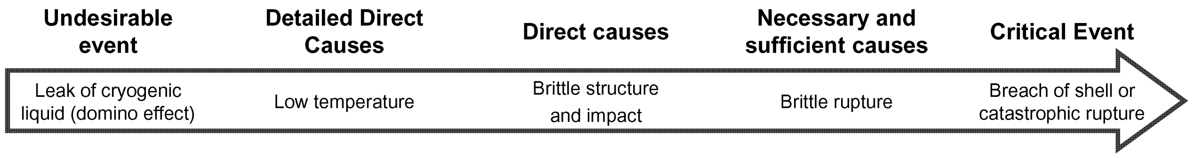


Fig. 1: example of chain of events triggered by release of cryogenic liquid.

in the bow-tie diagrams developed using the MIMAH procedure. Figure 3 show an example of results regarding accident scenarios following large leaks of LNG from a FSRU storage vessels.

The DyPASI procedure allowed the inclusion of atypical incident scenarios in hazard identification processes by a systematic procedure. Moreover, specific atypical incident scenarios that otherwise would not captured by common hazard identification techniques were detected. Finally the procedure also allowed a double check of the hazard identification process carried out using MIMAH, in order to determine if all the incident scenarios were described.

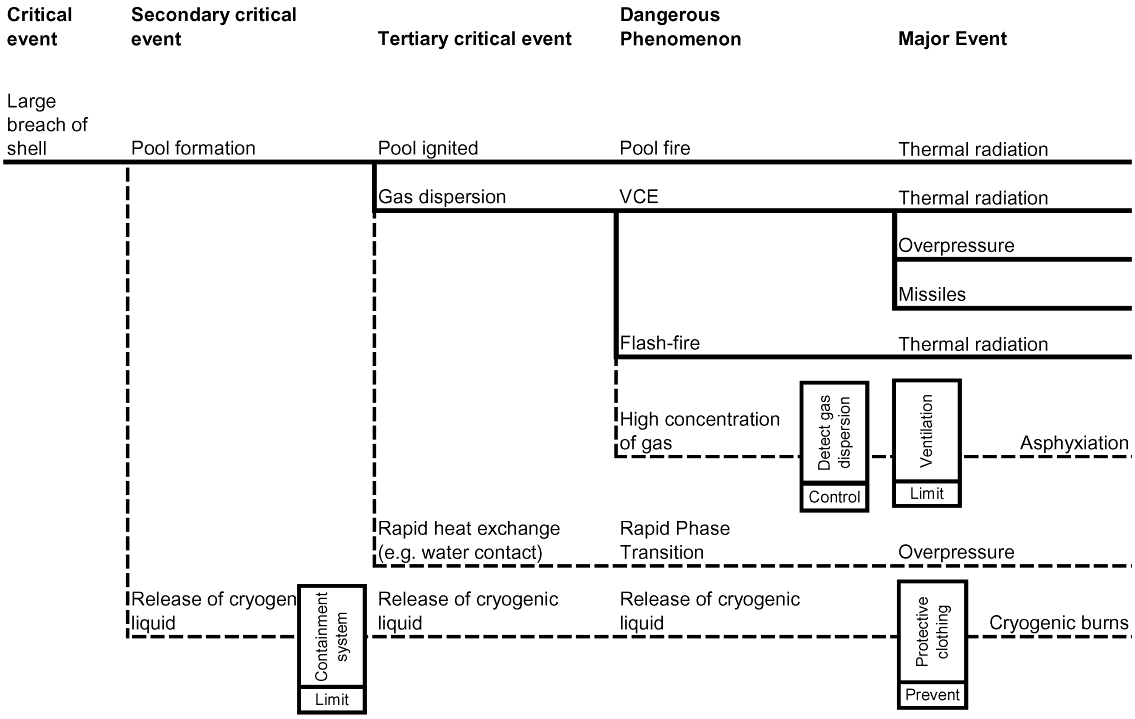


Fig.2: example of event tree section of the bow-tie diagram concerning a large breach of shell in the liquid phase of an LNG tank on a FSRU terminal.

2.3 HazId for external threats

HazId is a structured review technique based on brainstorming sessions. Although its guidewords are in part standardized (e.g. in ISO 17776 (ISO, 2000)) HazId relies mainly on the HazId leader and team experience to ensure a complete identification of threats during the brainstorming meetings. The guidewords usually adopted are detailed for what concerns “internal” or “intrinsic” hazards, but are left to a more general level of detail for what concerns hazards deriving from external actions or conditions. Within the Integ-Risk project, specific HazId sessions were dedicated to develop a list of guidewords and to identify a list of threats specifically dedicated to the identification of external threats for LNG regasification terminals. The brainstorming was carried out by an extended group of experts. An example of results is reported in table 2.

Application of such lists to reference installations evidenced as the more relevant hazards related to natural events are extreme weather conditions and flooding, which may lead to the potential loss of floating terminals (e.g. loss of mooring and ingress of water). Minor hazards related to the humidity and ice formation due to lower temperatures were identified. Considering man made events, significant hazards are related to the possibility of an external direct attack, by collision or by shooting the LNG tanks of FSRUs. Again, for floating terminals,

human error might be a critical issue due the fact that beside a specific training required by the plant personnel, similar to the one needed in fixed installations of the process industry, ship operation skills should be acquired.
For on-shore terminals, major hazardous natural events (e.g. flooding/tsunami waves) might lead only to minor losses of LNG. No major losses from storage tanks are expected due to resistance of the concrete secondary containment. For the same reason, external man-made events may result in a major impact only on the LNG carrier, moored on the jetty, rather than on the terminal itself. Hazards connected to the LNG carrier are therefore similar to the ones in offshore terminals. However, in onshore terminals the site location influences the possible hazardous interactions with other activities (e.g. railway, airports, motorways, etc.), which are not relevant in the case of offshore installations.

Table 2: Specific external threats identified for LNG terminals

HazId Guideword	Threat (Hazard) Offshore	Threat (Hazard) Onshore
Natural	Extreme weather (winds, waves)	Extreme weather (winds, waves)
	Tsunami	Tsunami/Flooding wave
	Ice	Ice
	Humidity	-
	Flooding	Flooding
	-	Soil movement/Erosion/Subsidence
Man Made	Direct attack	Direct attack
	Third Party activity	Third Party activity
	Dropped object	-
	Helicopter operation	-
	Human Factors	Human Factors
Structural stability/ positioning	Loss of position	Structure stability
	Sloshing	
	Loss of buoyancy	
Collision / impacts		Impact with plant vehicles

3. MODELS FOR CONSEQUENCE ASSESSMENT

3.1 Rapid Phase Transition explosion

Rapid Phase Transition can be the only cause of explosion if ignition does not occur after the accidental release of LNG on water. However, a high level of uncertainty is related to the modeling of this phenomenon. Many models have been put forward in the literature, each of them addressing specific aspects of the phenomenon, but none of them is capable of properly representing all the parameters involved. This is due both to the complexity of the phenomenology of the accident, and to the many different routes the accident can follow (scenarios), which are difficult to be predicted. Moreover, the scarce experimental data available do not provide useful insights on the phenomenon, sometimes providing conflicting information.

Assuming the occurrence of an explosion, if the calculation of the pressure profile is taken into consideration, only the classic TNT equivalency method was used for the estimation of the pressure profile as a function of the distance from the location of the release. However, significant physical differences exist for the two typologies of explosion. Starting from these considerations, a new approach was recently suggested, based on the use of the gas-dynamic similarity, by using acoustic model (Bubbico and Salzano, 2009). This approach has already provided interesting results in the study of the BLEVE explosion. However, important uncertainties in the quantification of the release rate, the mixing effect with water and the evaporation rate must be preliminarily solved in order to obtain a significant improvement in RPT modeling.

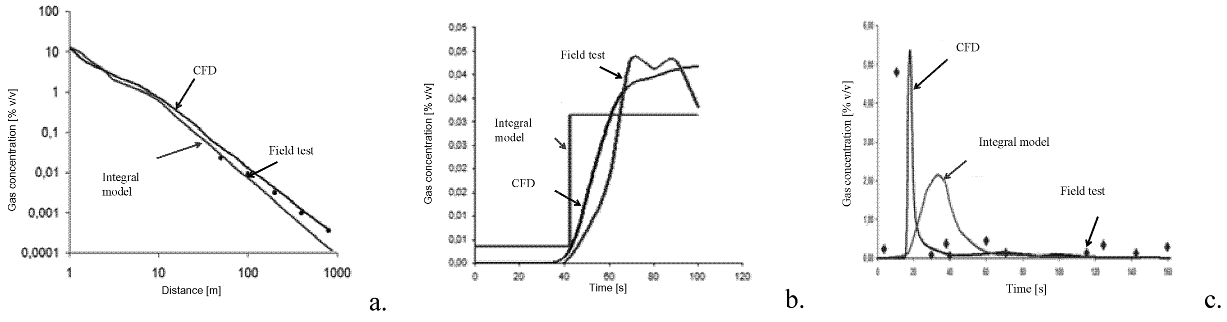
The acoustic evaluation of the pressure wave produced by a RPT of LNG released accidentally on water validated the safety distances reported by Sandia National Laboratory (Hightower et al., 2004), which has revisited LNG hazards focused on spills from ships onto water based on experiments. Significant impacts of a RPT of LNG on public safety and property are expected only for very large release rates (> 100 m^3min^{-1}) and are limited to distances lower than approximately 250m from the accidental spill source. This value may increase up to about 500m in the case of spills induced by “intentional” releases.

3.2 Best Available Model selection for Heavy Gas Dispersion

Among the potential consequences of LNG loss of containment in LNG regasification terminals, the formation and dispersion of flammable clouds has a particular relevance. In open field dispersions both integral models and CFD tools give accurate predictions. Thus, since CFD codes require a larger amount of resources, in open field, integral models should be preferred to obtain results in a relatively short time. When geometric complexity grows slightly CFD maintains good performances, while accuracy of integral models begin to fade; nevertheless, integral models should be still considered suitable for engineering purposes, and consequently still preferred. However, releases involving large obstacles have to be simulated by using a CFD approach in order to obtain accurate predictions.

These considerations derive from the simulations of three different set of experimental data with a growing geometrical complexity:

- Prairie Grass field tests: continuous releases of small amount of sulphur dioxide at or near ground level over a flat terrain. The experiments were carried out during both day and night leading to a wide range of atmospheric stability conditions; Figure 1a shows for the sake of example the results obtained for PG 17 test (Hotl and Witlox, 1999).
- Coyote tests series: large LNG and liquid nitrogen releases performed at the Naval Weapon Center, China lake, CA, by NWC and LLNL jointly (LLNL 1983). Dispersion took place in open field, roughly flat terrain, but LNG was spilled over a large water basin placed 1.5m below the surrounding ground level, onto a metallic spill plate; at the edge of the depression turbulent eddies were generated. In neutral/stable stratification (that characterized the Test 3 of the series, here analyzed), turbulence generated by this geometrical feature is particularly relevant for dispersion calculations. Figure 1b shows the results obtained for Test 3.
- Thorney Island field: performed by HSE (Health and Safety Executive), US Coast Guard, and the Department of Transportation, mainly divided into three phases: Phase I open field instantaneous releases, Phase II: instantaneous releases with obstacles and continuous releases in open field, Phase III: continuous releases both with and without obstacles. Among the large number of experiments, Test n. 26 has been used (McQuaid 1985-1987). Test n. 26 were performed during Phase II; in this trial, to mime an isolated building, a cube of 9m edge was used. The released gas was a mixture of Refrigerant-12 diluted with nitrogen. During the trial execution, wind speed was relatively low (1.9m s^{-1}) and the stratification was stable. Figure 1c shows the results obtained for Test n. 26.



a. b. c.

Figure1. Comparison between experimental data, CFD and UDM simulations for: a. Prairie Grass, b. Coyote 3 at 200 m, c. Thorney Island 26

The results sketched in Figure 1 clearly show an evident trend in the behavior of integral model: in open field dispersions, like Prairie Grass (a), both integral model and CFD tools give accurate predictions and integral models should be preferred to obtain results in a relatively short time. When geometric complexity slightly grows, like Coyote tests (b) CFD maintains good performances, while accuracy of integral models begin to fade and finally, in presence of large obstacles, like Thorney Island (c), only the CFD is able to make accurate predictions.

Therefore, a general methodology to discriminate between CFD and integral models for risk assessment of scenarios involving obstacles would be very useful. Missing such a methodology can lead to inaccurate predictions and, consequently, inadequate mitigation systems (underestimation of the cloud size due to the use of integral models on geometrical complex scenarios), or waste of resources (application of CFD to simple geometries, where integral models grant good results). For the sake of example, the influence of an obstacle on the dispersion of an heavy gas cloud is reported in Figure 2; these simulation have been performed using Falcon 3 experiment of the “Falcon series”. Performed by the Lawrence Livermore National Laboratory, in the Nevada’s desert, USA (Brown et al., 1987). Figure 2a shows the cloud LFL/2 (half of the Lower Flammability Limit) distance in open field, while Figure 2b shows the influence of a wall (height 16m and width 90m) placed at 100m from the fence on the LFL/2 distance. The cloud length was reduced by the 30% with respect to the open field.

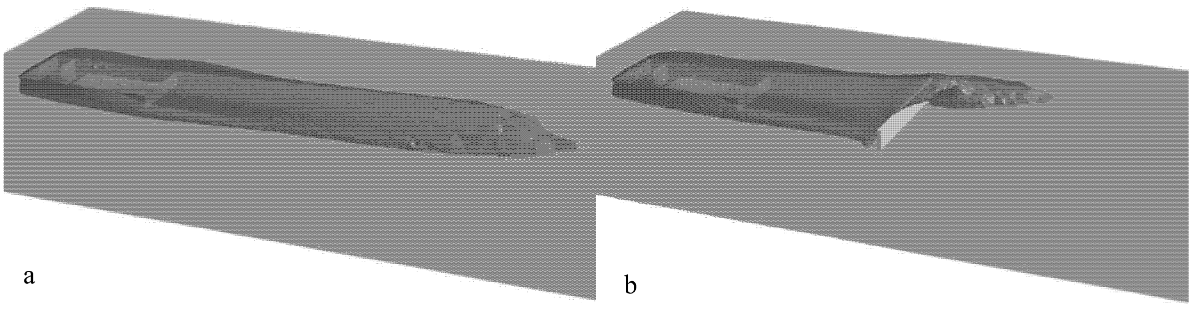


Figure 2. Cloud maximum LFL/2 distance a. in open field and b. in presence of a wall

Consequently a parametric analysis has been performed, and differences between gas cloud size in open field and in presence of an obstacle were studied. In the proposed methodology, the parameters analyzed were the obstacle geometry and position; dimensionless parameters have been defined in order to make data obtained in different simulations comparable. Simulations have been carried out in neutral stratification, with a 5 m s^{-1} wind (5D) and with two series of obstacles, changing the value of the parameters. The results clearly pointed out that integral models are inaccurate when large obstacles are involved. The dimensionless parameters defined were capable to define a region where such models are highly inaccurate depending on the geometry of obstacles. Thus, a procedure was defined for a first screening of the scenarios that require the use of CFD tools to obtain reliable predictions of cloud dispersion (Busini, to be submitted).

Such a procedure has been applied also to a case study showing both the influence, on the dispersion of clouds produced by massive release of LNG, of large obstacles present in a real LNG regasification plant and the effectiveness of mitigation barriers (Busini, submitted). It has been found that large obstacles influence cloud dispersion reducing the damage distance more than 50% compared to an open field release. The results on passive protection measures effectiveness indicate that height and position of the wall have a great importance and are strongly related to the cloud dimensions in open field. They can influence both positively and negatively the cloud behavior; this means that a mitigation barrier must be correctly designed, in terms of both location and height, to be effective in mitigating the accident consequences.

4. CONCLUSION

An important effort was dedicated within the iNTeg-Risk project to develop guidelines for the assessment of scenarios related to accidents in LNG regasification terminals. Relevant results were obtained both in the development of improved specific hazard identification techniques and in the identification, further development and assessment of best available models for consequence analysis.

5. ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support received from the EU within the 7th FP iNTeg-Risk project (CP-IP-213345-2)

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